Opportunity cost of CO2 emission reductions: developing vs. developed economies

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Resumen

Presentamos evidencia empírica sobre convergencia en magnitudes medioambientales para países desarrollados y en vías de desarrollo. Además, partiendo de un modelo standard "putty-clay" de uso de energía, introducimos un stock de contaminación sobre el que se fija un objetivo de reducción de emisiones. El análisis teórico ofrece indicaciones sobre qué variables deberían ser objeto de futuros acuerdos de reducción de emisiones entre países heterogéneos.

Palabras clave: economía medioambiental, convergencia, reducción de emisiones.

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Abstract

We present some empirical evidence on convergence of environmental magnitudes for a pool of developing and developed countries. Additional, we enlarge a standard model of energy use with putty-clay technology in order to allow for a stock of pollution, on which a target on emission reductions is set out in finite horizon. The theoretical analysis offers some insights on what variables should serve as basis of emission reduction target agreements among heterogeneous parties.

Key words: environment economy, convergence, emission reductions.

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1. Introduction

To promote international coordination on CO2 emission reductions is nowadays -in one way or another- at the forefront of the environmental policy of virtually any country in the world. This coordination has been so far materialised as the signing of agreements by sovereign countries to commit themselves to reduce their respective CO2 emissions. From the raw perspective of a theoretic economist, this is a tragedy of the commons problem: there is no supranational entity that can enforce countries to sign, the costs of reductions are individually paid -at a country level- and its benefits are worldwide collected. This being so, it seems natural that road map to the signing of the agreement be not a pleasant walk.

This paper addresses one of the most controversial issues of that road map. Because the concerned countries' economies are heterogeneous, we all agree that the emission reductions should be heterogeneous across countries as well. But the devil is in the details: what do we exactly mean by heterogeneous economies? and how that heterogeneity should be mapped into heterogeneity in the emission reductions?

The previous two questions summarize the two main objectives of this paper, and their order mimics the order in which they are analyzed. The first is rather positive whereas the second has clearly a normative angle. Our approach in the positive part is to take data for a pool of countries which are a priori -yet in a vague sense- heterogeneous and apply well-known econometric techniques at use, estimation of convergence equations, to relate economic growth and pollution emissions. Perhaps the more paradigmatic example of heterogeneous economies is that of developed versus emerging economies. Additionally, we must bear in mind, if we are to stress heterogeneity between developed and developing economies, that developed economies should not be themselves too heterogeneous, and the like applies for their developing partners. All in all, our pool is composed of the G7-group and seven emerging Latin American economies[1].

The normative part of this paper takes a step beyond the econometrics. The previous part essentially measures the observed relationship between pollution emissions and economic growth, but: how does this relationship change when the economy is pushed further to accomplish a hypothetical emission reduction agreement? For that, we need to postulate how the agents of the economy will react to something that has not been experienced so far. In short, we need a theoretical model of growth and pollution. In the normative part of this work we use such a model together with well-known axiomatic concepts of bargaining in order to predict the likelihood of emission reduction agreements between the pool of countries under consideration[2].

The rest of the paper is organised as follows. Next section presents the numerical analysis. Sections 3 and 4 contain the model and the theoretical analysis, respectively. Section 5 concludes.

2. Empirical analysis

We have a balanced sample of 14 countries: the G7 group together with seven Latin American emerging economies. The former are Canada, France, Germany, Italy, Japan, United Kingdom and the United States of America, whereas the latter are Argentina, Brazil, Chile, Colombia, Mexico, Peru and Venezuela. For each country, we take per capita data on C02 emissions, energy consumption and GDP. All time series have yearly frequency, and the sample period is 1980 to 2006, both included[3].

In this part we essentially focus on the study of convergence across countries. The literature on convergence typically distinguishes two sorts of convergence, called beta and sigma convergence, respectively. Essentially, and

[1]The G7-group is conformed by Canada, France, Germany, Italy, Japan, United Kingdom and the United States of America. The Latin American countries we take are Argentina, Brazil, Chile, Colombia, Mexico, Peru and Venezuela. Both groups have been alphabetically listed.

[2]There is a branch of literature that explicits -and measures- how home markets within a country are connected themselves and uses that information to predict impacts of environmental policies. These are the so-called computable general equilibrium models. For the sake of tractability and since we want to focus on inter rather intra-country allocations, the spirit of this paper is to view each country as an atom: we look at its aggregate behavior regardless its internal economic structure.

[3] The data source are EIA for energy and emissions and IMF for GDP.

referred, for instance to per-capita emissions, by beta convergence we mean that countries with larger initial levels of emissions (at the start of the sample period) have experienced larger reductions in emissions thereafter. By sigma convergence we mean that the intra-period cross-country variance of emissions reduces over time. Roughly, beta convergence is convergence of the conditional expectation whereas sigma convergence is convergence of the unconditional variance of the time series under consideration.

The econometric study of convergence is presented in the tables at the end of the paper. We basically consider four variables: the combinations from CO2 and energy use (labelled as CO2 and ENE in the table, resp.) with per capita and intensity units (prefix PC and IN, resp.). The intensity of CO2 emissions are emissions per unit of GDP, and intensity of energy use has an analogous definition. In some tables we present also measures of convergence of per capita GDP in yellow columns as a benchmark.

We start with beta convergence. The Table 1 shows the result of cross-section regressions of the overall growth rate over the sample period against the initial level. A negative coefficient of the initial level indicates beta-convergence, also called absolute beta-convergence (see Sala-i-Marti(1996)). The first and the second column for each magnitude (PC-CO2, PC-ENE, IN-CO2 and IN-INE) show that coefficient without taking and taking into account GDP effects, respectively. The results on overall convergence are weak -to say the best- for variable measured in per capita units while they are more robust for the same variables measured in intensity units.

The table 2 takes a closer look on beta convergence. It shows time-series regressions for each country in which the yearly growth rate is regressed against previous year's level. As before, a negative coefficient associated to the previous year's level shows conditional beta convergence (the notation was firstly introduced by Sala-i-Marti(1996)). The first and third column for each magnitude show the corresponding coefficient without incorporating and incorporating per capita GDP as an additional regressor, that is, discounting GDP effects. The second and fourth columns are standard deviations of the corresponding coefficients. The table shows a pattern of convergence which is relatively stable across countries and across magnitudes, particularly if GDP is discounted.

Finally, table 3 shows results on sigma convergence. We present two measures. The first is standard on the literature on GDP convergence: the evolution of coefficient of variation along time. This is labelled as "sigma-con" in the table for each magnitude. It shows a slow reduction over time, which indicates sigma convergence, in sharp contrast with the evolution of "sigma-con GDP", in the yellow part, which is the same statistic referred to the GDP.

Additionally, table 3 presents a second measure on convergence: a standard inequality index, which is presented in the columns labelled as "ine-ind". For a given year, it is computed as the supreme norm of the cumulative normalized frequency of observed values and the corresponding one to a perfectly uniform distribution. Thus, the index lies in [0, 1] and the closer to zero, the closer both frequencies are or, equivalently, the lesser is the heterogeneity across countries. The results for this alternative measure are in line with those for the coefficient of variation.

Table1: overall convergente

	PC_CO2			IN_CO2	
	beta	**disc_GDP**		**beta**	**disc_GDP**
estim.	-0,09	-0,13	**estim.**	-0,39	-0,20
std	0,07	0,07	**std**	0,14	0,14
	PC_ENE			IN_INE	
	beta	**disc_GDP**		**beta**	**disc_GDP**
estim.	-0,09	-0,10	**estim.**	-0,37	-0,14
std	0,06	0,06	**std**	0,15	0,15

Table 2: beta convergence

	PC_CO2					
	beta_conv	std	beta_conv_disc	std	beta_GDP	std_GDP
CA	-0,21	0,13	-0,57	0,14	0,04	0,01
FR	-0,34	0,06	-0,31	0,07	0,02	0,01
GE	-0,04	0,06	-0,36	0,16	0,02	0,01
IT	-0,03	0,06	-0,51	0,18	0,00	0,01
JA	-0,03	0,07	-0,53	0,14	0,01	0,02
UK	-0,20	0,10	-0,40	0,17	0,04	0,01
US	-0,43	0,15	-0,57	0,16	0,03	0,01
AR	-0,23	0,18	-0,72	0,19	0,06	0,05
BR	-0,01	0,05	-0,40	0,12	0,04	0,02
CH	0,00	0,05	-0,48	0,15	0,05	0,02
CO	-0,43	0,17	-0,45	0,18	0,04	0,02
ME	-0,43	0,20	-0,61	0,20	0,05	0,03
PE	-0,16	0,10	-0,14	0,11	0,09	0,05
VE	-0,42	0,15	-0,38	0,17	0,01	0,09
	PC_ENE					
	beta_conv	std	beta_conv_disc	std	beta_GDP	std_GDP
CA	-0,12	0,11	-0,56	0,18	0,04	0,01
FR	-0,01	0,05	-0,39	0,14	0,02	0,01
GE	-0,15	0,07	-0,17	0,13	0,02	0,01
IT	0,00	0,04	-0,61	0,16	0,00	0,01
JA	-0,02	0,04	-0,32	0,13	0,01	0,02
UK	-0,18	0,11	-0,32	0,17	0,04	0,01
US	-0,22	0,13	-0,40	0,16	0,03	0,01
AR	-0,02	0,10	-0,81	0,15	0,06	0,05
BR	0,01	0,03	-0,27	0,10	0,04	0,02
CH	0,03	0,03	-0,61	0,13	0,05	0,02
CO	-0,39	0,15	-0,47	0,16	0,04	0,02
ME	-0,12	0,15	-0,86	0,21	0,05	0,03
PE	-0,17	0,10	-0,16	0,10	0,09	0,05
VE	-0,22	0,14	-0,61	0,14	0,01	0,09
	IN_CO2					
	beta_conv	std	beta_conv_disc	std	beta_GDP	std_GDP
CA	-0,13	0,05	-0,48	0,11	0,04	0,01
FR	-0,18	0,03	-0,26	0,06	0,02	0,01
GE	0,03	0,04	-0,19	0,09	0,02	0,01
IT	-0,14	0,08	-0,58	0,17	0,00	0,01
JA	-0,23	0,06	-0,26	0,09	0,01	0,02
UK	-0,04	0,03	-0,17	0,12	0,04	0,01
US	-0,07	0,02	-0,34	0,06	0,03	0,01
AR	-0,34	0,14	-0,42	0,14	0,06	0,05
BR	-0,07	0,06	-0,09	0,12	0,04	0,02
CH	-0,50	0,17	-0,51	0,17	0,05	0,02
CO	-0,10	0,10	-0,56	0,20	0,04	0,02
ME	-0,08	0,10	-0,81	0,18	0,05	0,03
PE	-0,15	0,14	-0,79	0,18	0,09	0,05
VE	-0,39	0,17	-0,37	0,16	0,01	0,09

Table 2: beta convergente

	IN_ENE beta_conv	std	beta_conv_disc	std	beta_GDP	std_GDP
CA	-0,02	0,05	-0,38	0,15	0,04	0,01
FR	-0,20	0,09	-0,50	0,15	0,02	0,01
GE	-0,01	0,03	-0,43	0,15	0,02	0,01
IT	-0,17	0,06	-0,34	0,12	0,00	0,01
JA	-0,34	0,09	-0,36	0,11	0,01	0,02
UK	-0,02	0,03	-0,57	0,16	0,04	0,01
US	-0,06	0,02	-0,37	0,08	0,03	0,01
AR	-0,27	0,10	-0,24	0,11	0,06	0,05
BR	-0,07	0,04	-0,03	0,09	0,04	0,02
CH	-0,50	0,16	-0,50	0,16	0,05	0,02
CO	-0,13	0,13	-0,72	0,19	0,04	0,02
ME	-0,13	0,10	-0,31	0,11	0,05	0,03
PE	-0,27	0,18	-0,93	0,18	0,09	0,05
VE	-0,24	0,10	-0,18	0,14	0,01	0,09

Table 3: sigma convergence and inequality

	PC_CO2 sigma_con	ine_ind	sigma_conGDP	ine_indGDP		IN_CO2 sigma_con	ine_ind	sigma_conGDP	ine_indGDP
1980	0,83	0,32	0,49	0,22	**1980**	0,42	0,15	0,49	0,22
1981	0,82	0,32	0,50	0,22	**1981**	0,41	0,16	0,50	0,22
1982	0,80	0,31	0,51	0,23	**1982**	0,39	0,15	0,51	0,23
1983	0,81	0,32	0,53	0,24	**1983**	0,37	0,15	0,53	0,24
1984	0,83	0,32	0,54	0,25	**1984**	0,37	0,14	0,54	0,25
1985	0,83	0,32	0,56	0,26	**1985**	0,37	0,15	0,56	0,26
1986	0,83	0,32	0,55	0,25	**1986**	0,37	0,15	0,55	0,25
1987	0,84	0,32	0,55	0,26	**1987**	0,38	0,15	0,55	0,26
1988	0,85	0,33	0,57	0,26	**1988**	0,37	0,15	0,57	0,26
1989	0,84	0,32	0,59	0,28	**1989**	0,37	0,14	0,59	0,28
1990	0,83	0,32	0,60	0,28	**1990**	0,36	0,14	0,60	0,28
1991	0,81	0,32	0,58	0,27	**1991**	0,35	0,14	0,58	0,27
1992	0,82	0,32	0,58	0,27	**1992**	0,36	0,14	0,58	0,27
1993	0,82	0,32	0,57	0,26	**1993**	0,35	0,14	0,57	0,26
1994	0,82	0,31	0,57	0,26	**1994**	0,36	0,14	0,57	0,26
1995	0,81	0,31	0,57	0,27	**1995**	0,36	0,14	0,57	0,27
1996	0,80	0,30	0,57	0,27	**1996**	0,36	0,14	0,57	0,27
1997	0,80	0,30	0,56	0,26	**1997**	0,36	0,13	0,56	0,26
1998	0,79	0,29	0,57	0,26	**1998**	0,35	0,13	0,57	0,26
1999	0,80	0,30	0,59	0,27	**1999**	0,34	0,13	0,59	0,27
2000	0,80	0,30	0,59	0,28	**2000**	0,34	0,13	0,59	0,28
2001	0,79	0,30	0,60	0,28	**2001**	0,36	0,13	0,60	0,28
2002	0,81	0,31	0,61	0,28	**2002**	0,39	0,14	0,61	0,28
2003	0,81	0,31	0,61	0,28	**2003**	0,38	0,14	0,61	0,28
2004	0,80	0,31	0,60	0,28	**2004**	0,36	0,13	0,60	0,28
2005	0,79	0,30	0,59	0,27	**2005**	0,35	0,13	0,59	0,27
2006	0,78	0,30	0,58	0,27	**2006**	0,33	0,12	0,58	0,27

	PC_ENE					IN_ENE			
	sigma_con	ine_ind	sigma_conGDP	ine_indGDP		sigma_con	ine_ind	sigma_conGDP	ine_indGDP
1980	0,89	0,32	0,49	0,22	**1980**	0,46	0,15	0,49	0,22
1981	0,87	0,32	0,50	0,22	**1981**	0,44	0,15	0,50	0,22
1982	0,86	0,31	0,51	0,23	**1982**	0,43	0,15	0,51	0,23
1983	0,86	0,32	0,53	0,24	**1983**	0,42	0,15	0,53	0,24
1984	0,87	0,32	0,54	0,25	**1984**	0,41	0,15	0,54	0,25
1985	0,88	0,32	0,56	0,26	**1985**	0,40	0,14	0,56	0,26
1986	0,87	0,32	0,55	0,25	**1986**	0,41	0,15	0,55	0,25
1987	0,87	0,32	0,55	0,26	**1987**	0,41	0,15	0,55	0,26
1988	0,89	0,32	0,57	0,26	**1988**	0,40	0,14	0,57	0,26
1989	0,88	0,32	0,59	0,28	**1989**	0,40	0,15	0,59	0,28
1990	0,86	0,32	0,60	0,28	**1990**	0,38	0,14	0,60	0,28
1991	0,84	0,32	0,58	0,27	**1991**	0,39	0,14	0,58	0,27
1992	0,85	0,31	0,58	0,27	**1992**	0,40	0,14	0,58	0,27
1993	0,84	0,31	0,57	0,26	**1993**	0,40	0,14	0,57	0,26
1994	0,84	0,31	0,57	0,26	**1994**	0,41	0,15	0,57	0,26
1995	0,84	0,31	0,57	0,27	**1995**	0,40	0,15	0,57	0,27
1996	0,83	0,31	0,57	0,27	**1996**	0,40	0,15	0,57	0,27
1997	0,82	0,30	0,56	0,26	**1997**	0,40	0,14	0,56	0,26
1998	0,80	0,29	0,57	0,26	**1998**	0,39	0,14	0,57	0,26
1999	0,82	0,30	0,59	0,27	**1999**	0,38	0,14	0,59	0,27
2000	0,81	0,30	0,59	0,28	**2000**	0,37	0,13	0,59	0,28
2001	0,79	0,29	0,60	0,28	**2001**	0,38	0,14	0,60	0,28
2002	0,81	0,30	0,61	0,28	**2002**	0,40	0,14	0,61	0,28
2003	0,81	0,30	0,61	0,28	**2003**	0,40	0,14	0,61	0,28
2004	0,81	0,30	0,60	0,28	**2004**	0,38	0,14	0,60	0,28
2005	0,80	0,29	0,59	0,27	**2005**	0,38	0,13	0,59	0,27
2006	0,78	0,28	0,58	0,27	**2006**	0,36	0,13	0,58	0,27

3. Theoretical model

In this section we present a theoretical model in order to predict the countries' behavior when facing emission reduction targets. The model must satisfy two essential characteristics. First, we look for a model able to reproduce -at least qualitatively some observed facts related to pollution. Second, because an emission reduction target is essentially an emission ceiling and a deadline at which it must be hit, a finite-time horizon should be handable within our setting.

We basically build on Atkenson and Kehoe (1999). Greenhouse gas emissions are inevitably connected to energy use or, more exactly, to the use of those energy types that have served as a basis for economic growth worldwide along the recent decades. The model proposed by Atkenson and Kehoe delivers a basic feature observed in the use of those types of energy: it reacts very slowly to changes in energy prices[4]. Their theoretical explanation to that fact is as follows. In the economy there is a state of knowledge represented by a list of possible capital types. Each type must be used together with energy in a fixed proportion, and that proportion varies across types. Now, at any given moment in time it is given the histogram of capital types, that is, it is given how many units of each capital type are there, and all the economic agents can do in the short run is to use energy accordingly. In the long run, by making type-specific investments, the agents can modify the shape of the histogram. Taking up this central idea, we basically departure from Atkenson and Kehoe in two directions. First, we include a mapping from energy use to pollution emissions. Second, they mostly perform an analysis of the steady state of the economy, whereas we need to make some different -and standard- assumptions on

[4] Because in our model we want to focus on the effect of pollution emission targets on the countries behavior, we do not include energy prices in our model. Precisely the relatively low short run elasticity to energy prices justifies to neglect the effect of those prices in a finite horizon analysis.

the functional forms in order to allow for a finite horizon analysis[5]

We consider continuous time, indexed by t (with $t \geq 0$). Time subscript is omitted where it is unambiguous. There are two types of capital in the economy, denoted by k_p and k_a, respectively. If each type of capital is characterized by the proportion in which it uses energy, and energy use generates pollution, we claim that each capital type is equivalently defined by the amount pollution it generates per unit of capital. Let p be the stock of pollution in the economy, we assume its dynamics is given by

$$\dot{p} = \tau p + h(k_p) - g(k_a) \tag{1}$$

where $\tau \geq 0$ is the natural abatement rate and h and g are strictly increasing and differentiable functions with $h(0) = g(0) = 0$. In words, k_p generates pollution whereas k_a generates abatement. In addition, we assume k_p generates output according to some standard production function f whereas k_a does not. Output can be allocated either to consumption or to type-specific investment. Denoting consumption by c and j-type investment by xj (being j ™ $\{p, a\}$), the feasibility constraint of the economy is

$$f(k_p) \geq c + x_p + x_a \tag{2}$$

In turn, the dynamics of the j-type of capital is

$$\dot{k}_j = -\delta k_j + x_j \tag{3}$$

where δ is the depreciation rate, assumed constant across capital types[6]

Our model economy is ruled by a representative agent that obtains utility exclusively from consumption and does not obtain disutility from pollution[7]. Let us denote by u its instantaneous utility function and by r to the time discount parameter. Finally, an emission reduction target is essentially a pair $(T, \bar{p})$, which indicates that the stock of pollution at time T cannot exceed $\bar{p}$. Let us suppose that such a target is signed at time 0, being $T > 0$. Then the problem for the agent is

$$\max \left\{ \int_0^T e^{-rt} u(c_t) + \sum_j b_j k_{j,T} \right\} \tag{4}$$

subject to $p_T \leq \bar{p}$, the feasibility constraint (2) and the dynamics (3) and (1). The second term in (4) is a post-target salvage value. Roughly, the agent anticipates that life will go on after the agreement deadline and consequently he values to get to that time with some positive amounts of capital. The value for j-type capital is b_j.

4. Analysis of the model

4.1. THE BASIC FORCES

In order to apply the model to the data, we need to assume concrete functional forms. That will be done in the next subsection. Before such specific assumptions come into scene, we find convenient to perform some analysis in order to stress the essential effects we have included in our theoretical setting. This is the purpose of this subsection.

Once an emission reduction target is fixed, our model is a deterministic finite horizon optimal control problem. Although kept to a minimum, the use of some terminology of optimal control eases the presentation. The next proposition shows that our model delivers a standard consumption vs. investment trade-off together with also an standard equal revenue to investment across capital types rule.

Proposition 1. Let n denote the current-value co-state associated to pollution.

Under the optimal policy of (4) subject to (1), (2) and (3), it is

[5] In fact we are not even studing the transitional dynamics towards a steady state. We discuss more on this issue latter on.

[6] Our two-type economy is an extremely simplified case of Atkenson and Kehoe's model, who consider an arbitrary set of capital types. While adding complexity to the analysis, we claim that a further generalization in this direction does not bring new insights to our central question.

[7] 7As mentioned, greenhouse gas emissions are a tragedy-of-the-commons-problem: the cost of reducing emissions are individually paid whereas benefits from reductions are worldwide collected. Here we adopt the point of view of a single country: it must make an effort to reduce its emissions, whose stock is given by p, but only the aggregate stock across all countries enters its utility. If the country is small enough, such aggregate stock can be taken as a constant and thus omitted from the objective function.

$$-\frac{u''(c)}{u'(c)}\dot{c} = f'(k_p) - (\delta + r) + n\frac{h'(k_p)}{u'(c)}$$
$$-\frac{u''(c)}{u'(c)}\dot{c} = -n\frac{g'(k_a)}{u'(c)} - (\delta + r) \qquad (5)$$

In addition, it is $n_t < 0$ and $n'_t < 0$ for all t and also

$$f'(k_p)u'(c) + nh'(k_p) = -ng'(k_a) \qquad (6)$$

The proof is left to the appendix. Assume to start that there is no emission target and, consequently, there is no investment in k_a. Then (5) with $n = 0$ drives the basic dynamics of the economy, reflecting the usual rule in the dynamics of the consumption as a function of the stock of productive capital, k_p.

Now we introduce a target on emission reduction and, therefore, some investment in k_a is necessary[8]. There is an immediate consequence. At any point in time, an additional increase in the stock of pollution obliges to additional investment in k_a and, inevitably, to additional reductions in consumption. In short, an additional increase of pollution at any point in time worsens the functional objective, and that is what the negative sign of n_t accounts for. In addition, its time derivative is negative simply because the latter the additional increase in pollution takes place, the lesser time is left to make it compatible with reaching the target. The latter term in (5) is negative, indicating that if k_p were exogenously fixed at its no-target level at every t, then increases in consumption would be smaller (or reductions would be larger) than its no target counterpart simply because some consumption should be re-allocated to further investment in k_a.

The equation (6) is just a rule for the dynamics of consumption in terms of k_a as well. In essence, the standard rule in a capital accumulation model without pollution compares the time derivative of consumption with the marginal productivity of capital net from depreciation and time discount. This is (5), where the marginal productivity of k_p is not only the first term in the right hand side, but also its marginal effect on pollution, embodied in the latter term of its right hand side. And that is also (6), where the first term of the right hand side is the marginal productivity of k_a. Finally, direct comparison of (5) and (6) leads to (7), which states that the marginal productivity of k_p and k_a, left and right hand side, respectively, must equal each other at every t.

4.2. TARGETS AND DYNAMICS

In this subsection we assume the following functional forms: $U(c) = \ln(c)$, $f(k_p) = k_p^{\alpha}$, $h(k_p) = \theta_h k_p$ and $g(k_a) = \theta_g k_a$. Under these functional forms, the dynamics can be solved for c such that, from Proposition 1, we have:

$$\dot{c} = -n\theta_g c^2 - (\delta + r)c \qquad (7)$$

Consequently, the consumption reduces monotonically over time in the economy. Equation (8) shows the rate of reduction in consumption depends on parameters of the model (eventually different across countries), whereas its final level depends on the targets on emissions. More interestingly, for a given target, the final level on consumption depends crucially on k_p / k_a, that is, the ratio of productive to abatement capital. In order to solve the dynamics of the model, notice that once a solution in c to (8) is given, we obtain straightforwardly the evolution for k_p from (7). From it, the evolution for k_a is given by

$$\dot{k}_p + \dot{k}_a = -\delta(k_p + k_a) + f(k_p) - c \qquad (8)$$

which is nothing but the evolution of the aggregate stock of capital in the economy. Now, given an evolution for both types of capital, the evolution for p is given by (1), for which the target constitutes a boundary condition.

The dynamics can be synthesized in a phase-diagram in the k_p k_a plane. From a given initial point in it, that is, a pair of values (k_p, k_a), there is a unique trajectory that goes to a north eastern final point (thus increasing both types of capital), following the previous dynamics, in which the target is exactly met. We can also define a map of indifference curves with regard to the initial point. Roughly, any two distinct initial points placed in the same indifference curve lead the economy to different final north

[8] We assume implicitly that the emission target is not reached under a business-as-usual policy, that is, the target is not superfluous.

eastern points, but the representative consumer is indifferent among the consumption paths induced from those trajectories. Numerical analysis reveals that the indifferent curves are strictly increasing functions.

To understand the practical relevance of the previous analysis, notice that a pair (k_p, k_a) determines a unique value of the ratio

$$\frac{h(k_p) - g(k_a)}{f(k_p)} \tag{9}$$

The numerator are the emissions at a given instant, whereas the denominator is the total output of the economy, thus the ratio are the emissions measured in units of intensity. The previous analysis thus shows that the relevant variable to measure how much effort a country must make in order to met an emission reduction target is not given by its initial per capita emissions (assuming that our economy is composed by a single individual, that is just the numerator), but its initial intensity of emissions. So long as that ratio converges over time, as the analysis of the previous section suggests, there seem to be increasing reasons to have apparently different countries facing common-value targets.

5. Conclusions

We use standard econometric techniques on the study of convergence of environmental magnitudes for a pool of developing and developed countries. We also present a first attempt to build on a model of energy use to study finite-horizon targets on emission reduction agreements. Preliminary as it is, our analysis so far suggests that such agreements among targets should be contingent on a larger set of economic variables than what usually are.

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